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ENERGY CONVERSIONS IN A DEVELOPING CYCLONE

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ABSTRACT

A new Lagrangian method of determining energy conversion rates for individual cyclones is developed and applied to the rapidly deepening storm of Nov. 29–30, 1963.

It is shown that 12-hr average conversion rates can be determined for arbitrary volumes of the atmosphere that move with the velocity of the mean wind. The method is straightforward, relatively easy to apply, and eliminates the necessity of evaluating boundary flux terms and other quantities that are difficult to measure accurately.

The new Lagrangian method has the advantage of providing vertical profiles of the conversion rates that exhibit revealing temporal changes. It appears that the storm initially acquired kinetic energy in the lowest layers southwest of the center. Later, the largest kinetic energy increases occurred south of the center at intermediate levels. By the time the storm reached maturity, the largest increases were taking place at high levels northeast of the storm while kinetic energy decreases occurred below.

Finally, 36-hr isentropic trajectories are used to trace parcels backward in time for the purpose of determining the source regions of air characterized by large values of kinetic energy. The results of this analysis indicate that a preexisting source of kinetic energy associated with the jet maximum northwest of the storm provided part of the storm's energy; the remainder was generated locally as ascending air parcels accelerated northeastward from the nearly barotropic region in the warm sector of the cyclone.

1. INTRODUCTION

For as long as meteorologists have studied cyclones, these atmospheric systems have been recognized as regions in which kinetic energy is concentrated. But the precise mechanisms which supply storms with their energy are still not clearly understood. Of course, all motions of the atmosphere, including cyclones, are ultimately due to latitudinal differences in heat received from the sun. This heat, however, is not supplied directly to the storms; a portion of it is stored in the forms of internal and potential energy that can then be converted into energy of motion. The determination of exactly how and where this conversion takes place constitutes a fundamental problem in atmospheric science.

Early investigators concluded that energy conversions took place entirely within the cyclones through a process of overturning or readjustment of air masses. The first quantitative work concerned with the overturning process was performed by Margules (1910). Considering a closed system in which the total energy remained constant, he demonstrated that certain gravitationally unstable arrangements of two air masses with different densities could, through readjustment to a stable position, produce kinetic energy amounts comparable to those observed in middle-latitude storms.

Despite the fact that his results applied only to closed systems, Margules concluded that the production of kinetic energy in storms is also a direct consequence of in situ conversion of total potential energy. The fact that actual cyclones cannot be treated even approximately as closed systems has been discussed by Starr (1939, 1948), Phillips (1949), Rossby (1949), and Spar (1950).

An alternate mechanism for supplying kinetic energy to growing cyclones evolved from development of the theory of barotropic instability. Eliassen (1966) reviewed the relevant papers in this area and showed how the results of Kuo (1949) and Fjørtoft (1950) suggest that the kinetic energy of growing cyclones is taken from the available *kinetic* energy of the basic current. In a basic flow characterized by critical values of horizontal shear, the wave growth is related to a redistribution of preexisting vorticity.

Parallel investigations in the theory of baroclinic instability by Charney (1947) and Eady (1949) again drew attention to a mechanism whereby the baroclinity of storms effected a conversion of available *potential* energy to kinetic energy. That the two theories are in conflict regarding the source of kinetic energy has been pointed out by Eliassen who noted that there is both available potential and available kinetic energy present which can be exchanged for perturbation energy. It is probable that both mechanisms are important in providing kinetic energy to cyclones. It remains to assess quantitatively the extent to which both are effective in providing this energy.

Renewed interest in atmospheric energetics developed as a result of the studies of available potential energy by Lorenz (1955). He discussed the process of energy conversion and derived expressions for the conversion rates. But the concept of available potential energy has limited usefulness in the study of individual cyclones because it is difficult to define the available potential energy for an isolated region of the atmosphere. Moreover, even if a value of available potential energy could be specified, there is no assurance that all of this energy would be converted locally into kinetic energy. White and Saltz-

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man (1956) expressed the conversion rate as

$$\int_{V_p} \frac{dk}{dt} dV_p = -\int_{V_p} \left[\nabla_2 \cdot (\phi \mathbf{V}) + \frac{\partial}{\partial p} (\phi \omega) \right] dV_p - \int_{V_p} (\omega \alpha) dV_p. \tag{1}$$

Symbols in this report have the following meanings:

p pressure,
ω dp/dt,
ρ density,
ρ_θ $(-1/g)(\partial p/\partial \theta)$,
α specific volume,
g acceleration due to gravity,
M mass,
K kinetic energy,
k specific kinetic energy,
V volume (subscript denotes coordinate system),
T temperature,
θ potential temperature,
∇ del operator,
$\mathbf{V}$ horizontal wind vector,
$\mathbf{S}$ surface vector of an arbitrary volume,
$\mathbf{W}$ velocity vector of the boundary of an arbitrary volume, and
ϕ gz.

From equation (1), it is seen that kinetic energy increases in an arbitrary volume because of a net flux of energy into the volume and because of a local conversion of energy resulting from a direct circulation within the volume.

For studies of closed systems (the entire atmosphere, for example), the first integral on the right side of equation (1) vanishes, and the integral of the $\omega\alpha$ term represents the total rate of conversion between kinetic and available potential energy. It can easily be shown that the average value of $\omega\alpha$ becomes positive on any isobaric surface through which warm air is rising and cold air is sinking; but there is no assurance that $\omega\alpha$ represents the correct value for local conversion rates.

Saltzman and Fleisher (1961) made detailed analyses of the rate of kinetic energy change on a hemispheric basis by using the $\omega\alpha$ technique, in which case evaluation of the boundary terms was avoided. On the other hand, some investigators have ignored the boundary term even when working with open systems. Thus, Eddy (1965) applied a variation of the $\omega\alpha$ technique to a study of the distribution of conversion rates in a developing extratropical cyclone. By means of synoptic maps, Eddy showed that the kinetic energy production was most intense in the middle troposphere ahead of the storm and during the initial development. The total conversion rate was 10 w m^{-2}.

Kung (1966), expressing reservations about the practical accuracy of the $\omega\alpha$ technique, made a direct evaluation of the kinetic energy generation due to the work done by the horizontal pressure forces. By employing this direct approach, Kung avoided the difficulties involved in evaluating vertical velocities. To minimize the effects of spurious instantaneous measurements, he averaged the calculations over a 6-mo period. Kung obtained average generation rates of 8 w m^{-2}, but it is significant that the vertical profile of the conversion rates obtained were quite unlike Eddy's. Instead of a parabolic profile with a maximum value near 500 mb, Kung found maxima at both 300 mb and 900 mb, with a minimum at 500 mb. Both Eddy's and Kung's profiles of the conversion rates integrate to essentially the same total rate, as required by theory. Moreover, it may be that Eddy's and Kung's vertical profiles are compatible inasmuch as in one case certain boundary terms are included, while in the other case they are not.

At this point, it is clear that the study of cyclone energetics leaves a good deal to be desired. Kung's method of computing conversion rates is based upon long-term averages and thus was not applied to individual cyclones. The $\omega\alpha$ technique employed by Eddy and others can be applied to individual cyclones, but the method is inexact because the neglected boundary terms may be important and the vertical motions required for the calculations are at best questionable. It is the purpose of this paper to present a new and more exact technique for calculating energy conversion rates in restricted portions of the atmosphere.

2. THEORETICAL BASIS OF THE STUDY

The advantage of the method introduced here is that it permits determination of conversion rates in restricted portions of the atmosphere without requiring difficult calculations of boundary fluxes. The method is based on the fact that boundary fluxes need not be considered in the calculation of conversion rates for volumes that move isentropically with the velocity of the current in which they are embedded. It will be shown that these rates depend only on the time changes of kinetic energy in the volumes constrained to move in the manner prescribed above. To ensure that the kinetic energy changes are measured for the same mass of air, successive positions of the boundary of each volume must be determined by actual motions of the air parcels. Because these air motions are isentropic in at least some regions of a developing storm, isentropic trajectories can be employed to follow the volumes for which conversion rates are to be calculated.

The method used to construct isentropic trajectories for this study is identical to the one described in detail by Danielsen (1966). Although previous studies of cyclone energetics employed isobaric analyses, theoretical and practical considerations as discussed by Dutton and Johnson (1967) suggest that the use of isentropic analyses would be more appropriate. In isentropic coordinates, the time rate of change of kinetic energy, K, is defined as

$$\frac{dK}{dt} = \frac{d}{dt} \int_{V_\theta} (\rho_\theta k) dV_\theta. \tag{2}$$

By use of a variation of Leibniz's rule to differentiate integrals, it can be shown that

$$\frac{dK}{dt} = \int_{V_\theta} \frac{\partial}{\partial t} (\rho_\theta k) dV_\theta + \int_S d\mathbf{S} \cdot \mathbf{W} (\rho_\theta k). \tag{3}$$

If diabatic terms are neglected, (3) becomes

$$\frac{dK}{dt}=\int_{V_\theta}\left[\frac{d}{dt}(\rho_\theta k)-\mathbf{V}_H\cdot\nabla_\theta(\rho_\theta k)\right]dV_\theta+\int_S d\mathbf{S}\cdot\mathbf{W}(\rho_\theta k). \quad (4)$$

Application of the isentropic continuity equation and the divergence theorem permits equation (4) to be rewritten in the form

$$\frac{dK}{dt}=\int_{V_\theta}\rho_\theta\frac{dk}{dt}dV_\theta+\int_S d\mathbf{S}\cdot(\mathbf{W}-\mathbf{V})\rho_\theta k. \quad (5)$$

For cases in which the volume moves with the wind and if regions of strong turbulent mixing are avoided, it seems safe to assume that a reduced form of (5) can be employed with some justification in large areas of a developing storm. Equation (5) reduces then to

$$\frac{dK}{dt}=\int_{V_\theta}\rho_\theta\frac{dk}{dt}dV_\theta. \quad (6)$$

Equation (6) suggests at least two methods of calculating conversion rates in arbitrary volumes of the atmosphere. First, the left side of the equation can be evaluated simply by determining the difference between the initial and final values of the kinetic energy contained in a volume whose boundary moves with the air parcel trajectories. Because

$$K=\int_{V_\theta}\rho_\theta k dV_\theta=-\int_{V_\theta}\frac{1}{g}\left(\frac{\partial p}{\partial\theta}\frac{V^2}{2}\right)dV_\theta, \quad (7)$$

the time rate of change of kinetic energy is found by integrating and differencing values for the initial and final volumes. The time change of kinetic energy determined in this way represents an average value over a layer, the thickness of which is specified by the finite-difference interval chosen to evaluate ρ_θ.

The kinetic energies as evaluated by this procedure apply to volumes between two isentropic surfaces, say θ_1, and θ_2. Because the average motion of the entire volume can be approximated by the motion of an area on some intermediate surface, isentropic trajectories may be employed to determine the boundary of the final area which then represents the horizontal extent of the final volume. Of course, areas should be selected in regions of the cyclone where diabatic effects can be neglected, and an important check can be made on the calculations by determining if the mass of the moving volume is conserved.

An alternative method of calculating average conversion rates consists of evaluating the term on the right-hand side of equation (6). The change in kinetic energy per unit mass can be calculated from speed changes along trajectories. Values of $\overline{\rho_\theta}$ from consecutive isentropic charts must be averaged for each grid point in order to obtain values that correspond to the time of the average speed change. Because the values of $\overline{\rho_\theta}$ and dK/dt apply to the midtime between successive isentropic charts, their product must be integrated over a volume delineated by the midtime positions of the trajectories used to follow the volume.

The first of the two methods for computing conversion rates, hereafter referred to as the Lagrangian method, is the one selected in this study because it is more straightforward and subject to fewer errors than is the alternative method.

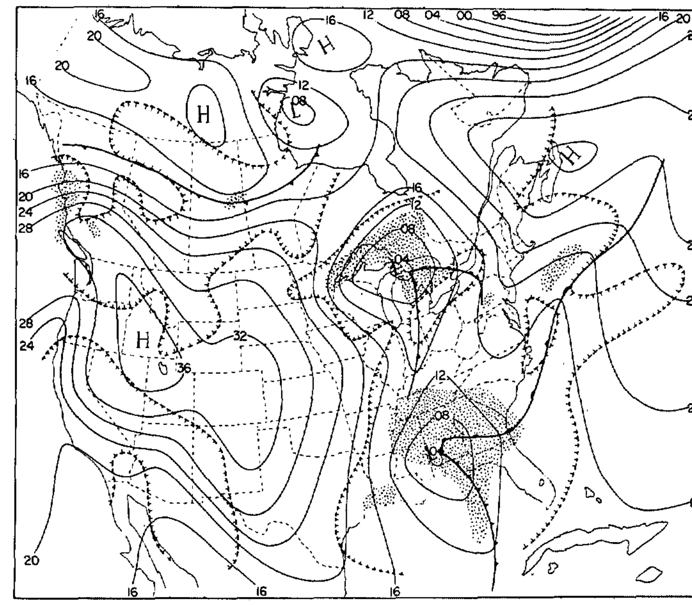

FIGURE 1.—Surface analysis for 0000 GMT on Nov. 29, 1963. Stippled areas designate precipitation; tick marks enclose areas where sky cover equals or exceeds three-quarters.

3. APPLICATION TO A DEVELOPING STORM

A principal advantage of the Lagrangian method of calculating energy conversion rates is that it can be applied to individual cyclones. The case under consideration here involves an intense extratropical cyclone that originated over the Gulf of Mexico and moved northeastward accompanied by moderate to occasionally heavy rain and strong wind. The four surface maps presented in figures 1–4 illustrate the progress of the storm at 12-hr intervals between 0000 GMT on November 29 and 1200 GMT on November 30, 1963. The intense development of the Gulf Low is evident in both the increasing pressure gradients and the large deepening rate which reached a value of 1 mb hr^{-1}.

A second storm, moving rapidly eastward from the Pacific Ocean along the northern border of the United States, accompanied the developing Gulf Low. The Pacific system is observed to lose its identity as the two storms merge over eastern Canada; but its role as a source of energy for the developing Gulf Low may have been important initially.

Analyses of eight isentropic surfaces ranging from 295°K to 325°K at 5°K increments were available for each of the four time periods examined in this study. Because the kinetic energy can be defined only for volumes in which the mass is known, calculations were made to provide distributions of a quantity which when integrated over a volume gives the total kinetic energy contained therein. These calculations are required in applying the Lagrangian method of finding average energy conversion rates.

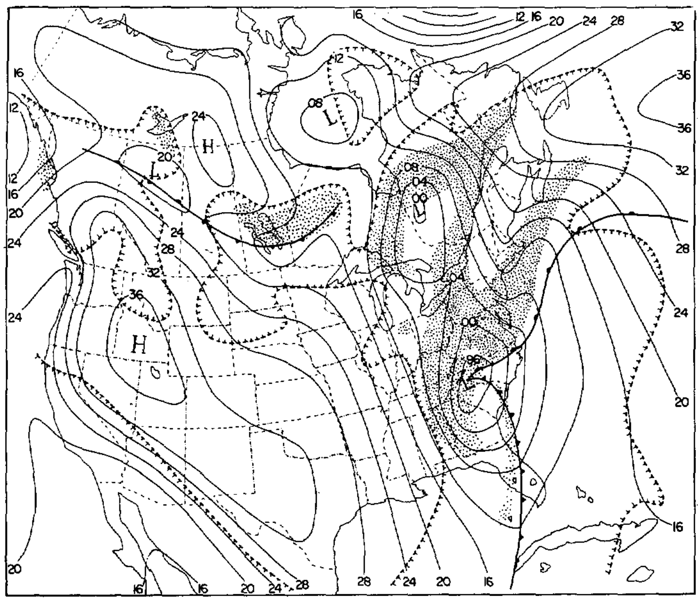

FIGURE 2.—Surface analysis for 1200 GMT on Nov. 29, 1963. See figure 1 for details.

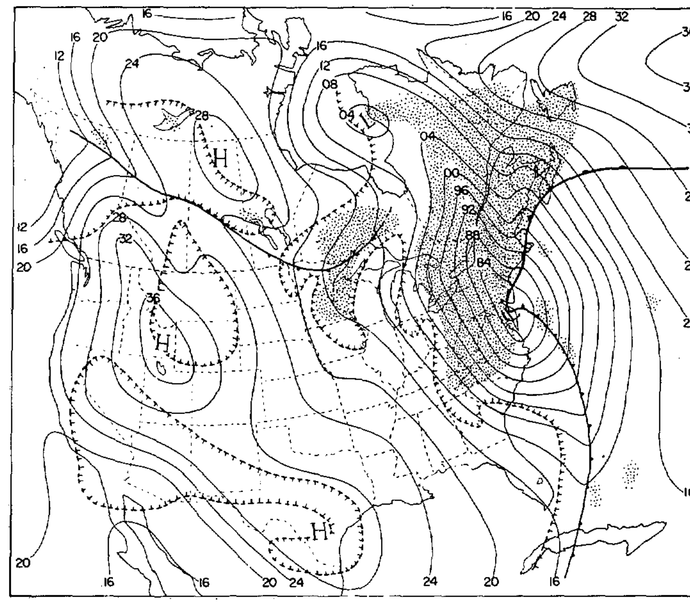

FIGURE 3.—Surface analysis for 0000 GMT on Nov. 30, 1963. See figure 1 for details.

From equation (7), it is seen that $\rho_\theta k$ is the quantity to be integrated; its value at grid points on the 305°K isentropic surface, for example, can be found by use of the equation

$$(\rho_\theta k)_{305}=\frac{1}{g}\left[\frac{p_{310}-p_{300}}{10}\right]\frac{V^2}{2}. \tag{8}$$

The availability of isentropic surfaces at 5°K increments made it convenient to calculate the kinetic energy for volumes having a vertical dimension of 10°K.

For each of the four time periods, charts of $\rho_\theta k$ were prepared for each of the five isentropic surfaces between 300°K and 320°K. The essential features of these analyses can be illustrated by considering those for a single intermediate level. The 305°K surface was chosen for this purpose because it is typical of the other levels and it does not intersect the ground in the area of interest. The distributions of $\rho_\theta k$ on the 305°K surfaces are presented in figures 5–8.

The most striking feature of these analyses is the manner in which values of $\rho_\theta k$ increase in the vicinity of the developing Gulf Low. The observed decreases and subsequent increases of the $\rho_\theta k$ maximum in eastern Canada correspond to alterations in the position of the jet maximum in that area. As the storm grows, the largest values of $\rho_\theta k$ remain fairly constant over the central part of the United States. The strength of the maximum in this region serves as a reminder that broad, nearly zonal currents can contain as much, if not more, kinetic energy than the most intense cyclones.

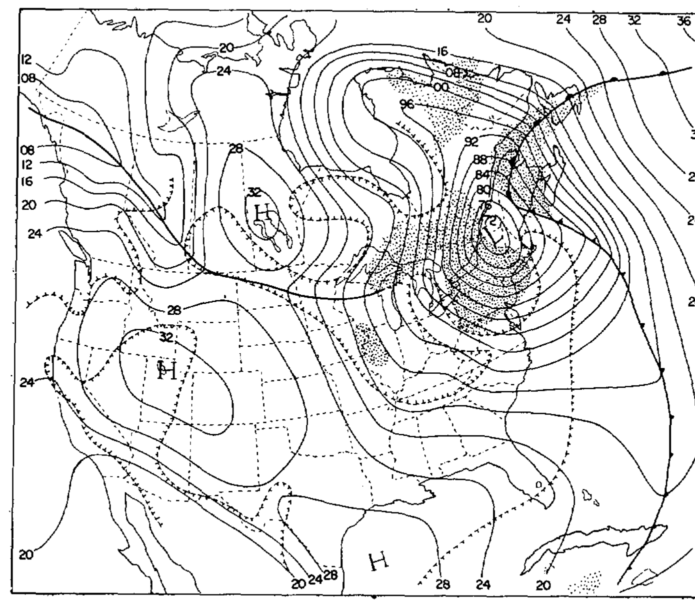

FIGURE 4.—Surface analysis for 1200 GMT on Nov. 30, 1963. See figure 1 for details.

PROCEDURE

The calculations of average conversion rates, or kinetic energy changes, in various volumes of the storm were carried out in accord with the procedure outlined below:

1) The $\rho_\theta k$ analysis for a particular period was examined and an area selected which enclosed a region of the storm characterized by large values of $\rho_\theta k$. For example, the area selected on the 305°K surface for 1200 GMT on November 29 is shown in figure 9A. The area chosen defines the horizontal extent of a volume between the 310°K and the 300°K levels for which the kinetic energy is calculated. Areas selected for the other two periods are shown in figures 10A and 11A.

2) Ten to 15 points along the boundary of the area selected in the first step were chosen as terminal points of trajectories that were then constructed according to the procedures described by Danielsen (1966). The origin points of the trajectories thus determined define an area on the initial $\rho_\theta k$ analysis in which the air in the final volume originated (0000 GMT on November 29, in this instance). Figures 9B, 10B, and 11B illustrate the initial and final

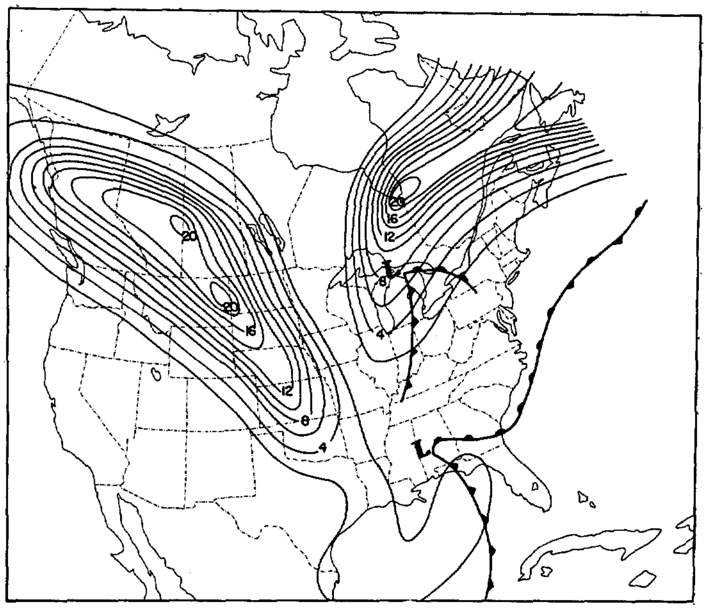

FIGURE 5.—The 305°K $\rho_\theta k$ analysis (10^7 gm sec^{-2} deg^{-1}) for 0000 GMT on Nov. 29, 1963.

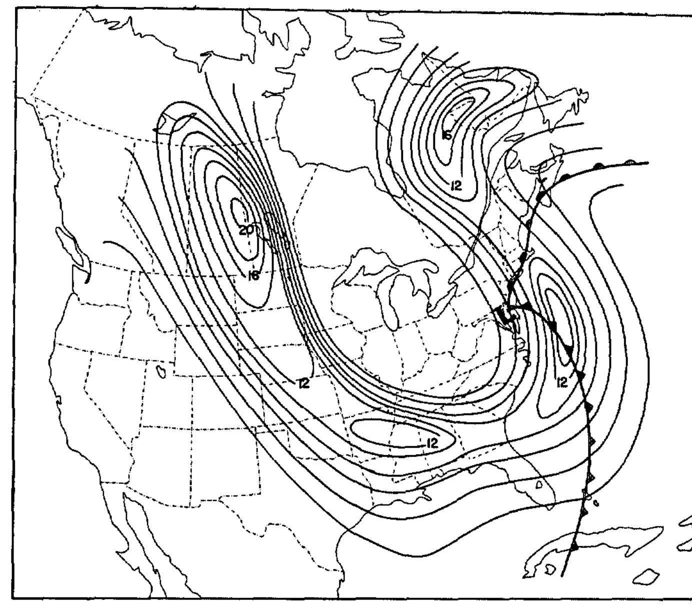

FIGURE 7.—The 305°K $\rho_\theta k$ analysis (10^7 gm sec^{-2} deg^{-1}) for 0000 GMT on Nov. 30, 1963.

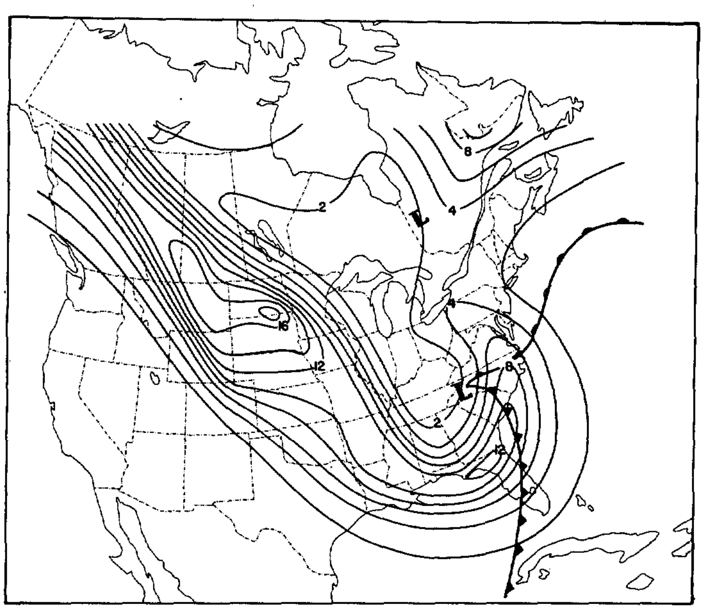

FIGURE 6.—The 305°K $\rho_\theta k$ analysis (10^7 gm sec^{-2} deg^{-1}) for 1200 GMT on Nov. 29, 1963.

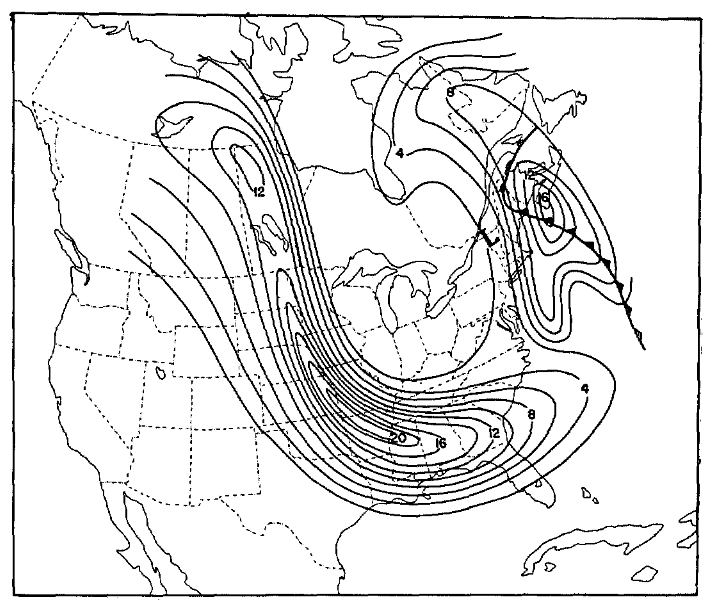

FIGURE 8.—The 305°K $\rho_\theta k$ analysis (10^7 gm sec^{-2} deg^{-1}) for 1200 GMT on Nov. 30, 1963.

areas along with samples of the relevant trajectories. Figures 9C, 10C, and 11C depict the positions of the resulting initial areas relative to the appropriate $\rho_\theta k$ analyses for the various periods.

3) The masses of both the initial and final volumes, defined by the areas outlined in the second step, are calculated by summing over all the grid points contained in the area, A. Thus, the mass is given by the equation

$$M=-\frac{1}{g}\sum_A\left(\frac{p_{310}-p_{300}}{10}\right). \tag{9}$$

Invariably, the masses of the final and initial volumes were found to agree within 10 percent. Thus it was assumed that the motion of the volume had been determined correctly and represented correctly the motions of the air parcels.

4) The kinetic energies contained in both the initial and final volumes were calculated according to the equation

$$K=\sum_A(\rho_\theta k). \tag{10}$$

5) The difference between the kinetic energies of the final and initial volumes was determined. These values, divided by the time interval of 12 hr, produced the average conversion rates for the various volumes examined.

The above procedure was repeated for each of the five isentropic levels used in this study. In repeating the first step for the other levels, the same areas as shown for the

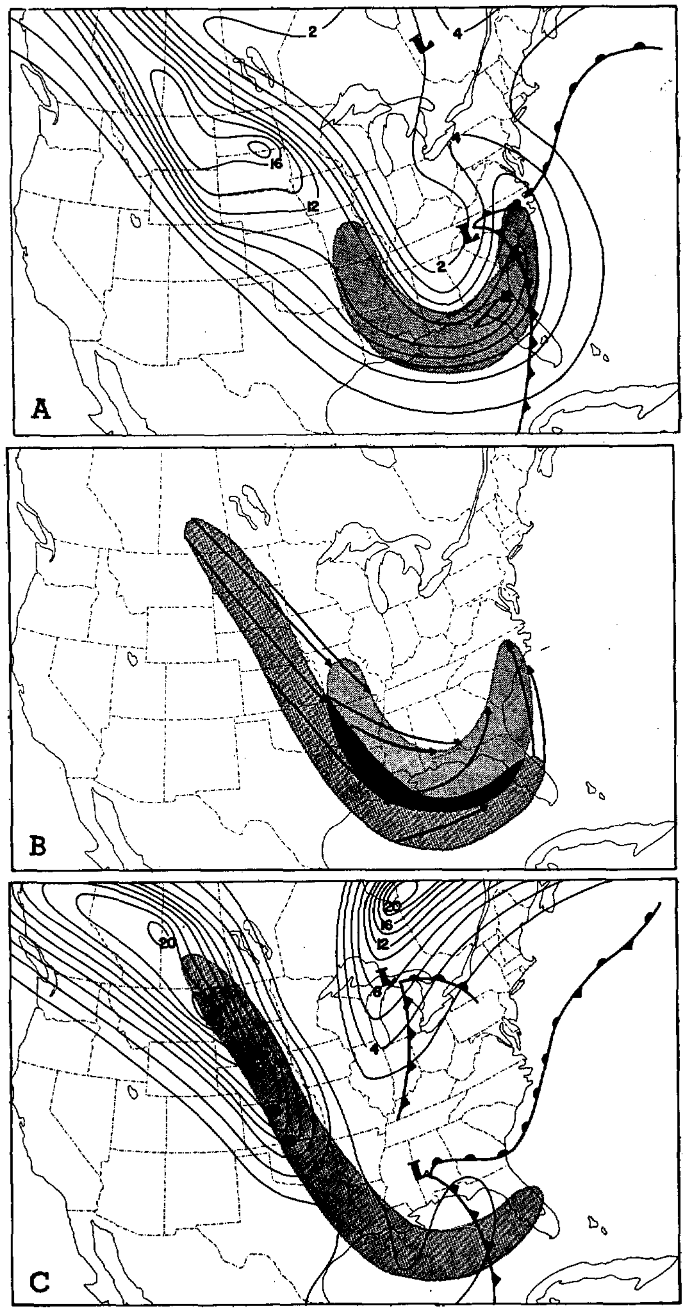

FIGURE 9.—Nov. 29, 1963, (A) 305°K final area selected (shaded) for 1200 GMT; (B) area change by trajectories for 0600 GMT; (C) 305°K resulting initial area (shaded) for 0000 GMT.

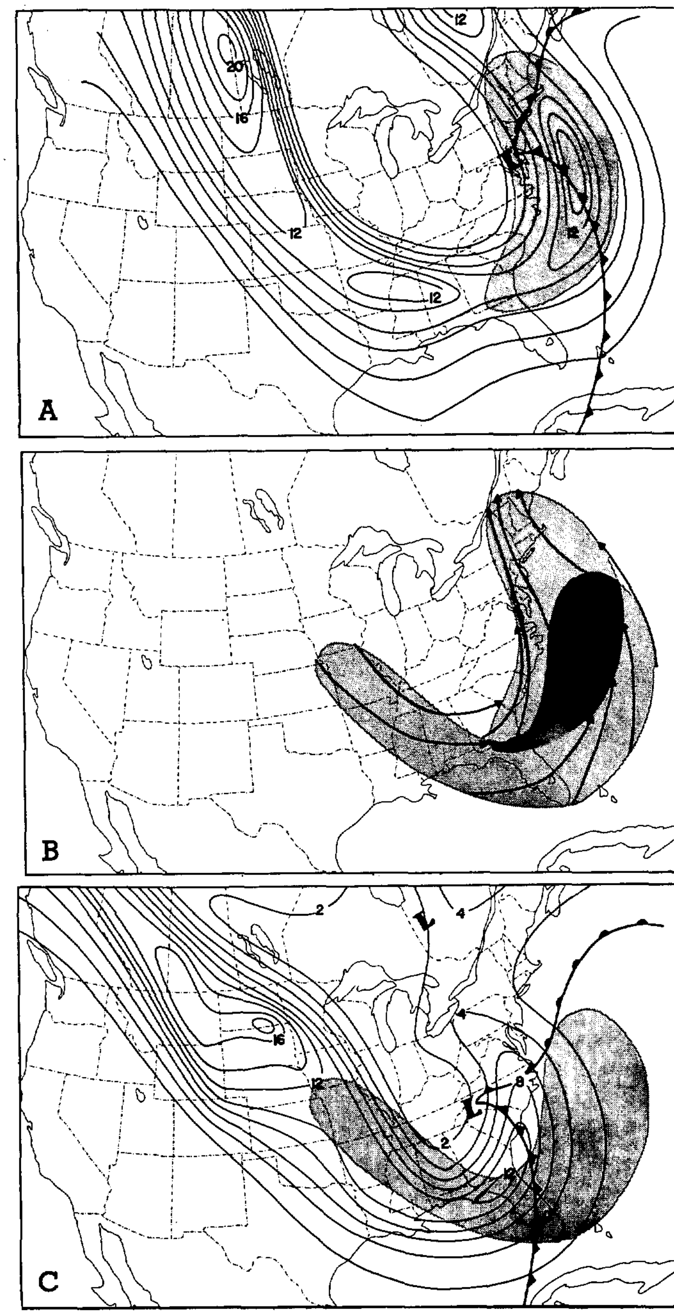

FIGURE 10.—Nov. 30, 1963, (A) 305°K final area selected (shaded) for 0000 GMT; (B) area change by trajectories for 1800 GMT; (C) 305°K resulting initial area (shaded) for 1200 GMT.

305°K analyses in figures 9A, 10A, and 11A were employed to obtain average conversion rates. In other words, the conversion rates were computed for volumes whose lateral boundaries were determined by the perimeter of the areas on the 305°K surfaces.

VERTICAL DISTRIBUTION OF CONVERSION RATES

The conversion rates calculated above represent time averages over the period between two observation times and can be considered to apply at the midtime. Thus for the period 0600 GMT on November 29, the mean conversion rate is known for each of the five layers, 10°K thick, between 295°K and 325°K. Similarly, the vertical distribution of mean conversion rates is known for the periods corresponding to 1800 GMT on November 29 and 0600 GMT on November 30. The results of all the calculations are summarized in the vertical profiles of the mean conversion rates shown in figure 12.

The profile for 0600 GMT on November 29, shown on the left of figure 12, illustrates the vertical distribution of mean conversion rates during the early stages of the storm's development. For this period, a maximum rate of 5.3 $\mathrm{w\,m^{-2}}$ is observed for the 315°K surface. The rate of conversion is seen to decrease both above and below the 315°K level, and there is a deep layer between 300°K and 310°K in which uniform rates of approximately 3 $\mathrm{w\,m^{-2}}$ are noted.

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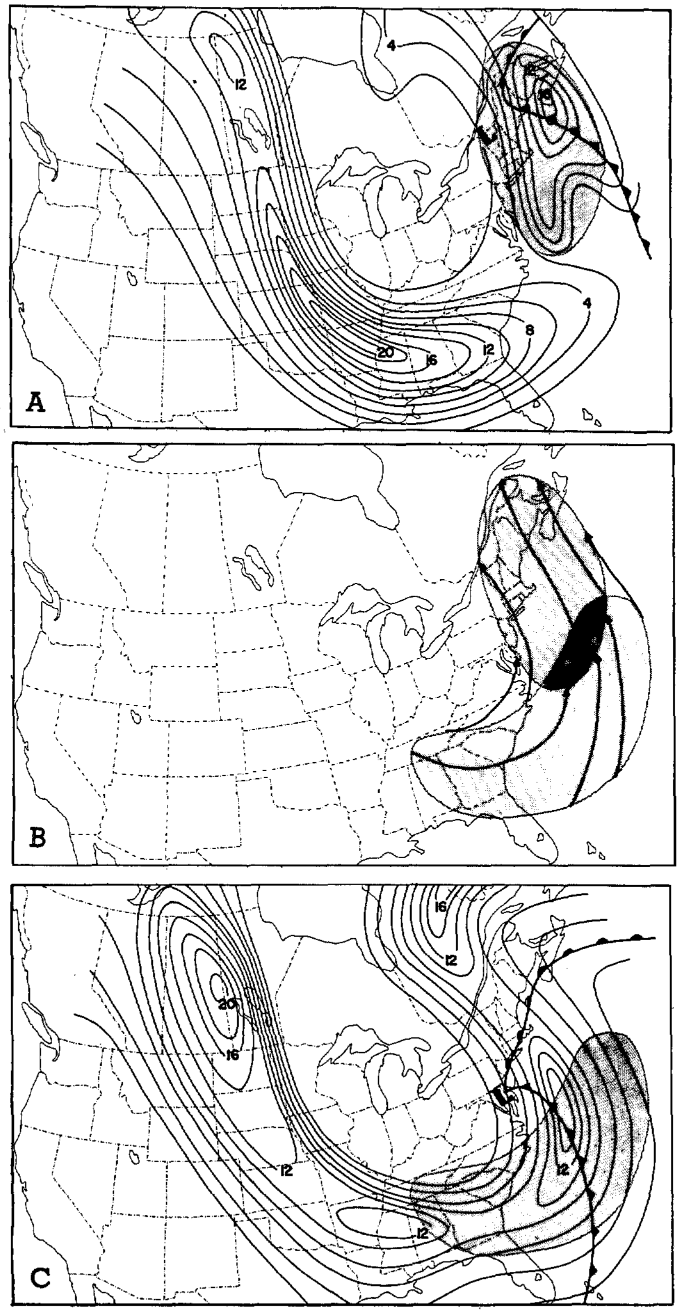

FIGURE 11.—Nov. 30, 1963, (A) 305°K final area selected (shaded) for 1200 GMT; (B) area change by trajectories for 0600 GMT; (C) 305°K resulting initial area (shaded) for 0000 GMT.

The conversion rates later in the development are shown by the profile for 1800 GMT on November 29. The level of maximum conversion has descended from 315°K to 310°K where a value of 4 w m^{-2} is observed. A secondary maximum of 2.8 w m^{-2} appears at 320°K. The layer between 300°K and 310°K is no longer characterized by uniform rates; the rate has diminished from 3 w m^{-2} to 1.1 w m^{-2} in the lower levels of the storm.

The final profile for 0600 GMT on November 30 depicts the mean conversion rates characteristic of the mature stage of the cyclone. The secondary maximum evident on the previous profile has become the predominant feature of the final one, and the rate exceeds 10 w m^{-2} in the neighborhood of the 320°K level. The primary maximum of the

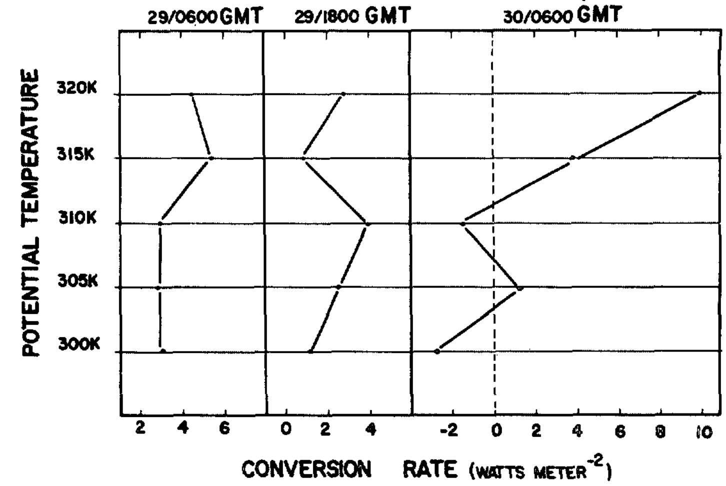

FIGURE 12.—Calculated average conversion rates (w m^{-2}).

1800 GMT November 29 profile apparently continues to descend another 5°K to the 305°K surface where a rate of 1.2 w m^{-2} is observed. This final profile shows that at both the 300°K and the 310°K levels kinetic energy is being destroyed. The storm is obviously reaching a dissipation stage during which the negative conversion rates reach values of -2.8 w m^{-2} at 300°K and -1.5 w m^{-2} at 310°K. The 315°K minimum of the 1800 GMT November 29 profile has descended to the 310°K level at 0600 on November 30.

The largest conversion rates during the first period occurred at relatively high levels. Later, maxima were observed at both intermediate and high levels. The lower maximum occurred at successively lower levels as the storm developed. Furthermore, dramatic increases of mean conversion rates at high levels of the 0600 GMT November 30 profile tend to support synoptic observations that energy production at higher levels presages dissipation of the upstream storm and development of a new storm downstream.

The total conversion rate found by integration over all levels of the storm for the first period is 18.5 w m^{-2}; for the second period, 11.1 w m^{-2}; and for the third, 10.9 w m^{-2}. These figures suggest that the largest conversion rates occur early in the development of the storm and decrease with time. However, these rates are not directly comparable, since different volumes were used for the three different periods; this was done to ensure that the maximum average rate would be obtained for any given period. Nevertheless, additional checks made by tracing a single volume through all time periods tend to confirm the observation that the largest conversion rates occurred early in the development of the storm.

THIRTY-SIX-HOUR ISENTROPIC TRAJECTORIES

Previous studies treating the problem of cyclone energetics have left unresolved the question of where the principal energy conversions take place relative to the developing storm. Adherents of the $\omega\alpha$ technique argue that the conversions must occur locally, in the vicinity of the low center, because this is where the vertical motions achieve their largest values and make the greatest contribution to the conversion process. Other investigators, basing their arguments on the results of the barotropic instability theory, maintain that the principal energy conversions occur in regions remote from the low center, and that the kinetic energy generated in these regions is subsequently advected into the developing cyclone. In this latter argument, the large reservoir of kinetic energy associated with a jet-stream maximum in the broad currents upstream is pictured as the primary source of kinetic energy.

That these two views are both partially correct is seen by examining 36-hr isentropic trajectories that trace the air motions through the storm under study. These 36-hr trajectories aid in determining the source regions of the air and indicate whether or not the air parcels underwent accelerations.

Trajectories traced backward on the 305°K isentropic surface from 1200 GMT on November 30 to their points of origin at 0000 GMT on November 29 are presented in figure 13. The shaded area centered near the New England coast corresponds to the region of the storm where the kinetic energy was concentrated during the mature stage. The trajectories show that the air in this region originated 36 hr earlier in a narrow band extending from the Midwest over the Gulf of Mexico to Cuba.

Clearly, the air parcels characterized by large values of kinetic energy at 1200 GMT on November 30 originated in widely separated sources. One source of the kinetic energy was obviously the jet maximum situated over southern Canada and Montana at 0000 GMT on November 29. Air parcels from this source generally decelerated as they moved into the vicinity of the cyclone. Nevertheless, their original values of kinetic energy were so large that they could provide energy to the developing storm. In contrast to these decelerating parcels, the trajectories from another source region south of the storm exhibit considerable acceleration.

The results of the analysis of the 36-hr trajectories suggest that a preexisting source of kinetic energy in the baroclinic region west of the storm provided only a part of the energy of the storm; the remainder was evidently generated locally as the air accelerated north and eastward from the nearly barotropic region in the warm sector of the original cyclone.

4. SUMMARY AND CONCLUSIONS

In the past, there has been considerable difficulty in developing satisfactory techniques for diagnosing energy conversions in individual cyclones. Numerous efforts have been made to circumvent these difficulties, but the two techniques currently employed for this purpose have not produced entirely satisfactory results. In one case, the effects of spurious observations have been eliminated by an averaging process; but the results do not then apply to individual storms. The other method requires difficult calculations of vertical motion, and its users have often ignored certain boundary terms that can be important. The present study represents an effort to overcome these limitations by introducing a new method of computing energy conversion rates for an individual cyclone.

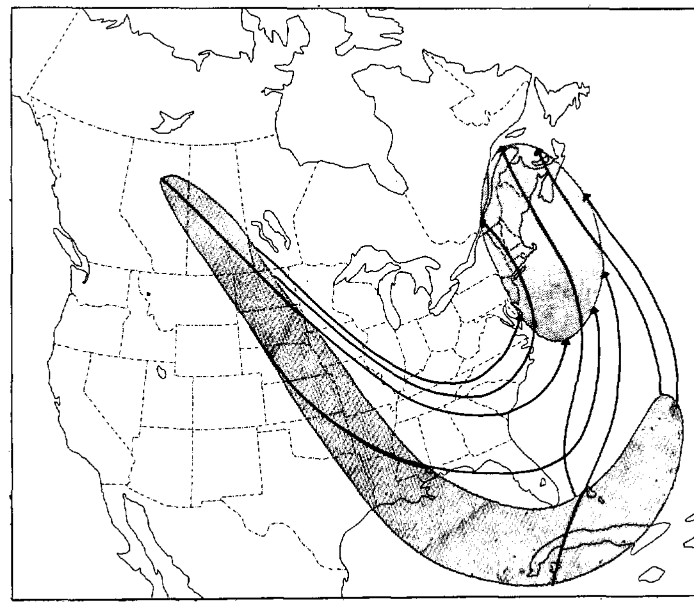

FIGURE 13.—The 305°K 36-hr isentropic trajectories.

The results of this investigation suggest that the observed energy changes for a particular storm can be related to a series of events that, taken collectively, provide an overall view of the development process. This view is presented here to summarize and interpret many of the implications of the entire study. The extent to which this interpretation applies to other cyclones remains undetermined; but at least a basis for comparison is established.

Thirty-six-hour isentropic trajectories for the November 1963 case reveal that the two principal sources of kinetic energy for the Gulf cyclone are: 1) the baroclinic region associated with a jet maximum in the northwesterly flow west of the trough and 2) the relatively barotropic region southeast of the trough in the vicinity of the warm sector of the cyclone. Although these sources are not necessarily independent, they are discussed separately below.

The intensity and position of the jet maximum associated with the developing cyclone is undoubtedly related to the existence upstream of an earlier cyclone that provided a mechanism for increasing the baroclinity through meridional displacements of air masses. The resulting thermal field favors intensification of the vertical wind shear and thus contributed to the strength of the jet maximum that subsequently became a source of kinetic energy for the storm developing downstream.

In some as yet unspecified way, this jet maximum propagates through the upsteam ridge and becomes connected with a Pacific Low that reached maturity just as the Gulf Low began its rapid development. The extent to which the Pacific Low contributed additional baroclinity to the jet suggests a possible link between the "parent" Pacific Low and the developing Gulf Low. There are undoubtedly other ways in which a parent cyclone is linked with a developing storm to the south; but such links are not evident from this study. The baroclinity is seen, in this connection, simply as an indication of the amount of available kinetic energy associated with the jet maximum in the northwest flow. This interpretation differs significantly from more popular notions.

With regard to the other kinetic energy source, namely, the barotropic region in the warm sector of the storm, it is possible that the parcel accelerations here result from the rapid deepening of the growing cyclone. The increasing gradients can play a large part in the acceleration of the air parcels as they ascend and move northeastward into a developing baroclinic zone east of the trough. Thus the accelerating parcels contribute to the intensity of a new jet maximum that develops at high levels downstream from the maturing storm. The large kinetic energy increases observed in the region ahead of the storm supports this interpretation.

Evidently, there are preferred regions in which the kinetic energy increases occur. From the vertical profiles of the conversion rate and the location of the volumes in which maximum conversion occurs, it appears that the storm initially acquired energy in the lower layers southwest of the center. Later, the largest kinetic energy increases occur south of the storm at intermediate levels. By the time the storm reaches maturity, the largest increases are observed at high levels while kinetic energy decreases are noted below. Throughout the development, kinetic energy was supplied by parcels accelerating in the immediate vicinity of the storm as well as by parcels that decelerated and descended from a large kinetic energy source upstream. It is interesting that, initially, the storm extracted some of its energy from a high-level source west of the center and, later, produced a high-level supply of kinetic energy to the east that could serve as an energy source for storm development downstream.

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